An Integrated Approach to Swept Wing Icing Simulation

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NASA/ONERA/FAA Swept Wing Icing Project

SUNSET II

Overall Goal

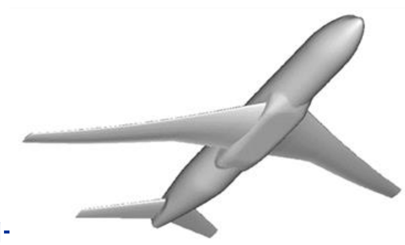
- Improve the fidelity of experimental and computational simulation methods for swept-wing ice accretion formation and resulting aerodynamic effect.

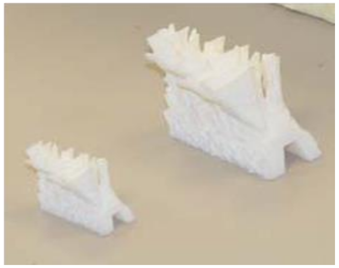
Objectives

- Generate a database of 3D ice-accretion geometry for icing-code development and validation; and for aerodynamic testing.
- Develop a systematic understanding of the aerodynamic effect of icing on swept-wings including: Reynolds and Mach number effects, important flowfield physics and fundamental differences from 2D.
- Determine the level of geometric fidelity required for accurate aerodynamic simulation of swept-wing icing effects.

Status

- Generated ice shapes in IRT on CRM model
- Aero testing in WSU low-Re wind tunnel – 2 campaigns
- Aero testing in ONERA F1 high-Re wind tunnel – 1 campaign

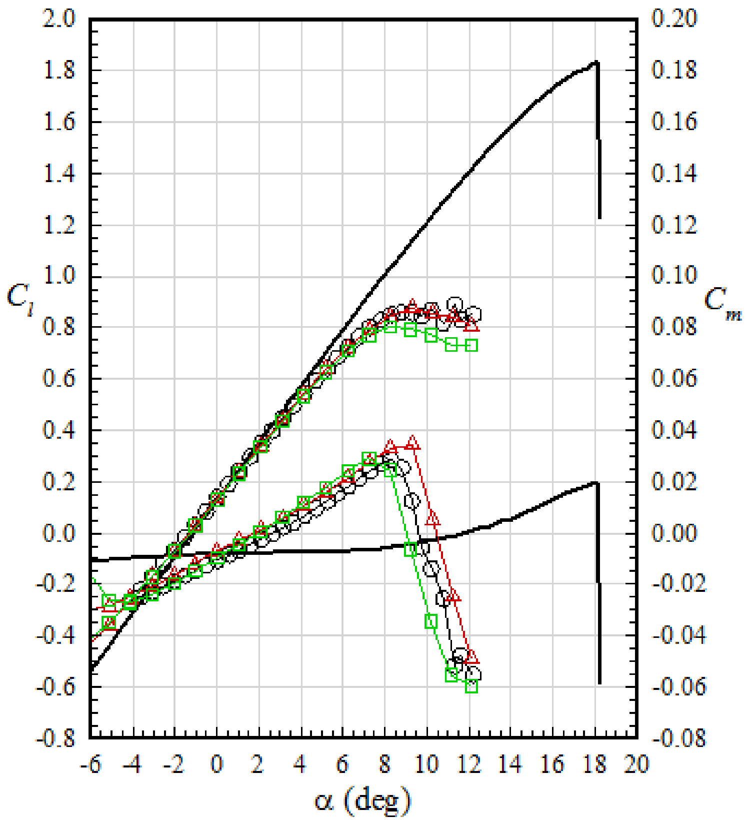


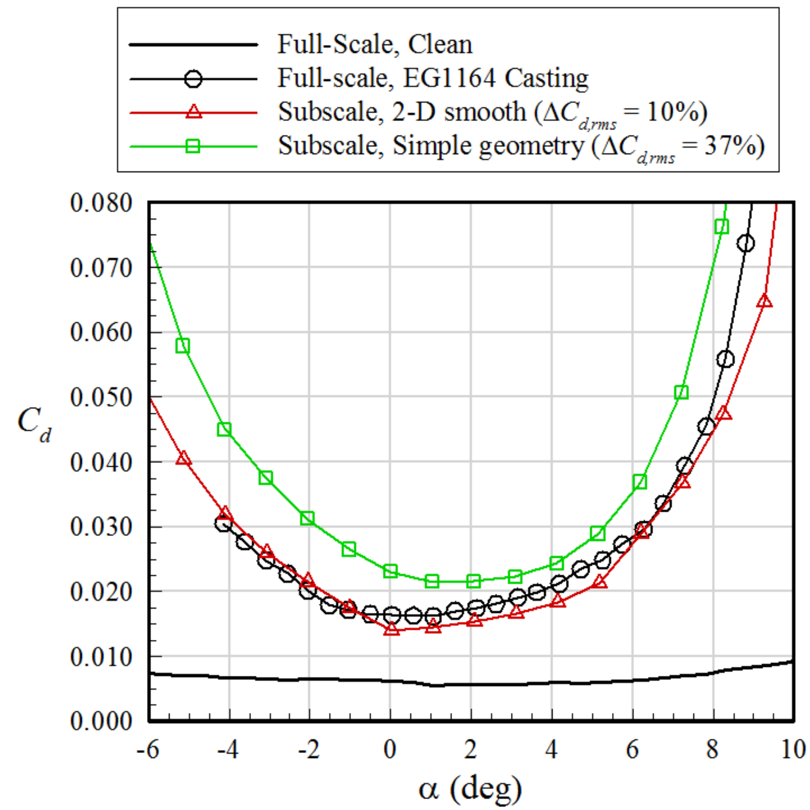


High and Lower Fidelity Models for the Same Ice Shape

- Previous efforts examined the influence of ice shape fidelity on the aerodynamics of constant cross-section airfoil models
- In general, results indicated that there were differences between realistic ice shapes and lower fidelity versions of such shapes
- This project was developed, in part, to determine the level of geometric fidelity required for accurate aerodynamic simulation of **swept-wing** icing effects.

Changes to Performance Characteristics from Leading Edge Ice Accretions





An Integrated Approach to Swept Wing Icing Simulation

What is meant by an integrated approach?

Use of various experimental and computational tools to piece together all the elements needed to reproduce ice growth and determine its aerodynamic impact in a realistic manner for a representative commercial transport aircraft

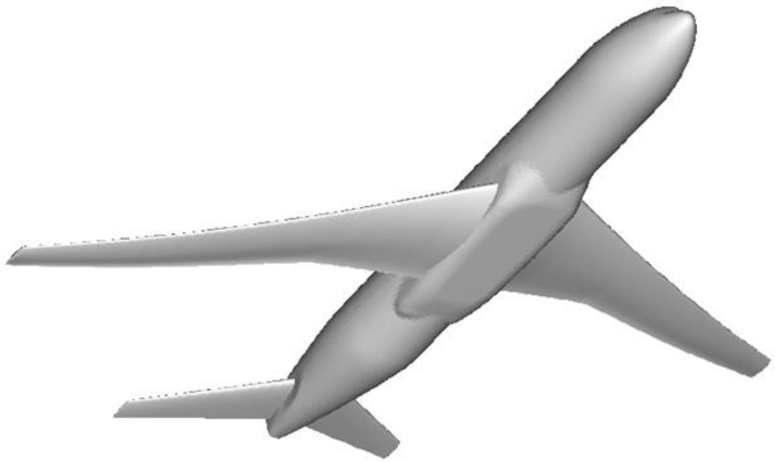
- Computational tools
  - Ice accretion codes
  - Airfoil design codes
  - Navier-Stokes CFD codes
- Experimental tools
  - Icing wind tunnel
  - Aerodynamic wind tunnels
  - Scaling methods
  - Ice shape measurement methods and model construction methods

An Integrated Approach to Swept Wing Icing Simulation

What did we do?

- Selected a representative wing model
- Identified how we were going to generate ice shapes
  - Selected stations along the span of the wing
  - Built “hybrid” models of those spanwise stations
  - Generated ice shapes at those locations and documented them with 3D laser scans
- Performed aerodynamic testing of the wing model with and without the ice shapes we generated
  - Built models of the wing for the low-Re and high-Re aero tunnels
  - Devised a method to create full span ice shapes from the ice shapes at the three spanwise stations
  - Built high fidelity and low fidelity full-span ice shapes for both the aero tunnels
  - Performed aero testing of the wing model with a clean leading edge and various high and low fidelity ice shapes at both aero tunnels

Model Selection (1 of 2)

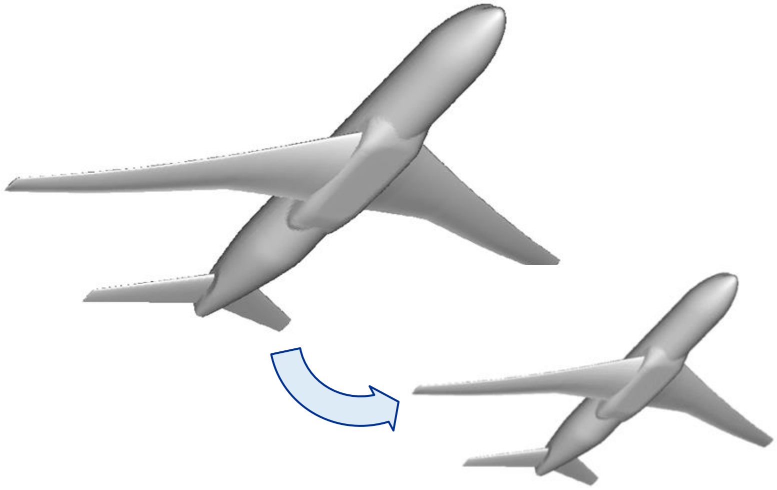


The Common Research Model was selected for this project.

- It represents a modern commercial transport category aircraft
- The 35° swept wing has a contemporary transonic super-critical design that is well behaved
- The geometry is publicly available, is non-proprietary and not export controlled

Airplane	Span, ft	Mean aerodynamic chord, ft	Area, ft^2	Aspect ratio(b)	Taper ratio(b)	Sweep angle, $c/4$
CRM	192.8	23.0	4,130	9.0	0.28	35°
Airbus A330-200/300	198.0	23.9	3,892	9.5	0.22	30°
Boeing 777-200	199.9	26.5	4,389	8.7	0.27	31°
Boeing 787-9	197.0	20.6	3,880	9.6	0.18	32°
Boeing 747-400	211.4	29.8	5,417	7.7	0.28	37°

Model Selection (2 of 2)



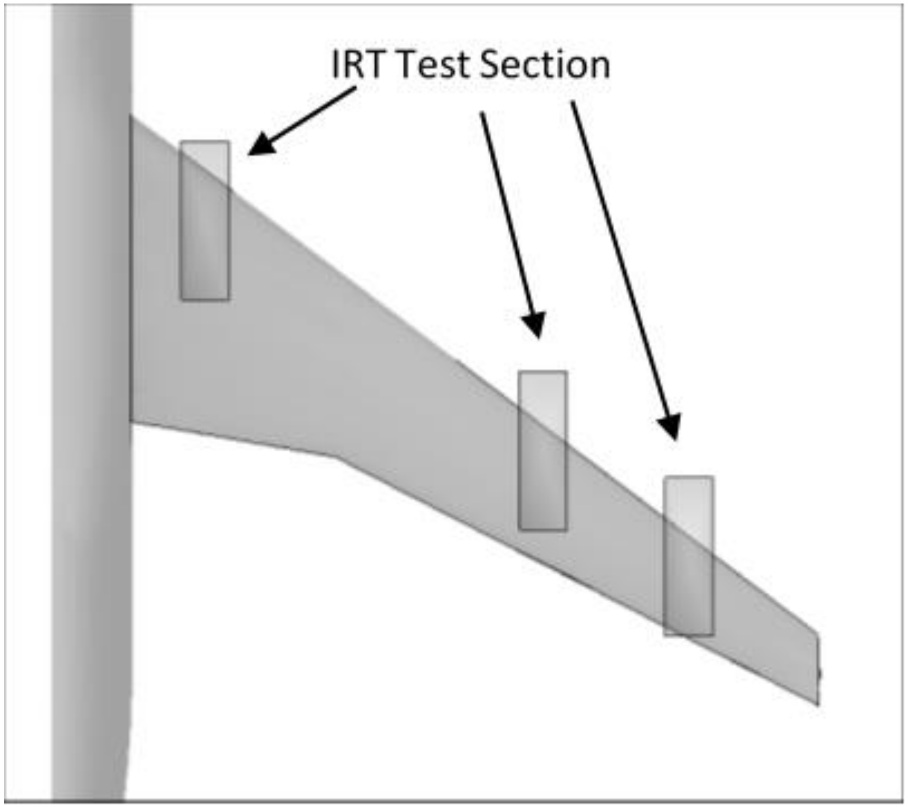
The CRM wing size presented challenges for both IRT and aero tunnel testing.

- The wing section model for the IRT would be an aggressive design
- Scaling of the ice shapes to fit on aero tunnel models would create extremely small ice shape models
- Roughness features of the ice shapes would not be captured in the artificial ice shape manufacturing process

A 65% scale version of the model was selected as the full-scale reference model for this project – CRM65

Airplane	Span, ft	Mean aerodynamic chord, ft	Area, ft^2	Aspect ratio(b)	Taper ratio(b)	Sweep angle, $c/4$
CRM65	125.3	15.0	1,745	9.0	0.28	35°
Airbus A320	112.0	14.1	1,320	9.5	0.21	25°
Boeing 737-800	112.6	13.0	1,341	9.5	0.16	25°
Boeing 757-200	124.8	16.7	1,847	7.8	0.21	25°

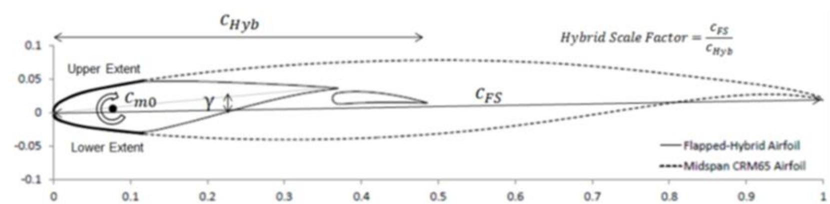
Full scale CRM65 wing overlaid with IRT test section planform outlines



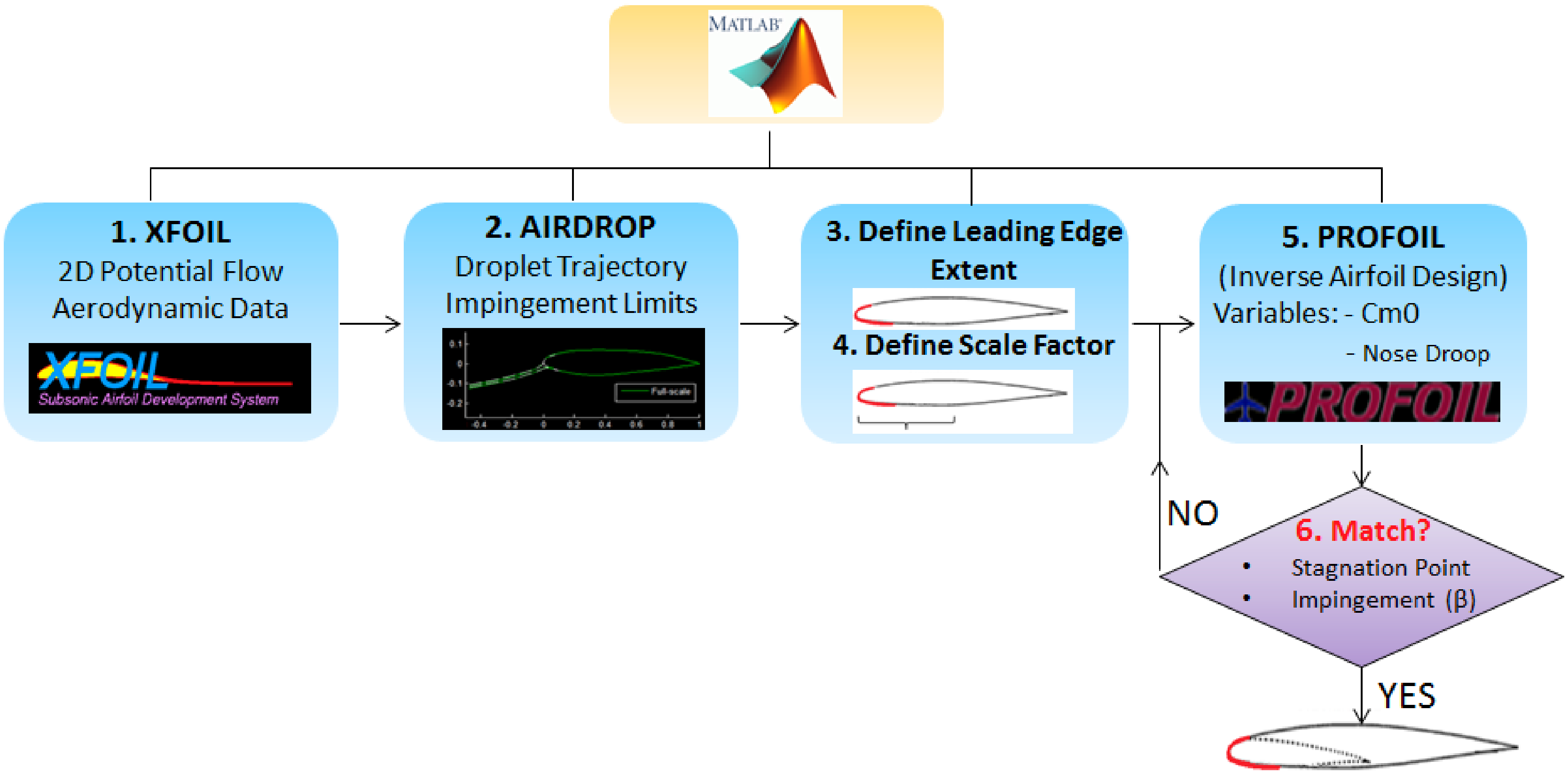
This diagram illustrates that full scale wing sections from the CRM65 would not fit in the Icing Research Tunnel.

A method for creation of an airfoil with a full scale leading edge and a truncated aft body for ice accretion testing was developed by Saeed, Selig and Bragg in 1997.

This method was extended in this project to the swept wing geometry of the three spanwise locations on the CRM65 selected for modeling.

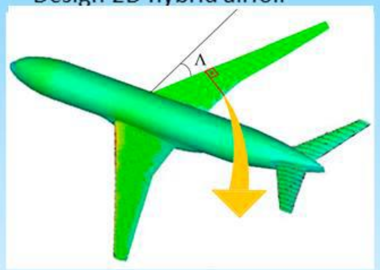


Hybrid Wing Model Design Method (1 of 3)

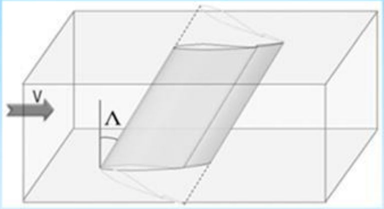


Hybrid Wing Model Design Method (2 of 3)

① HYBRID AIRFOIL
- Pick aircraft geometry reference
- Pick normal cut full-scale airfoil
- Design 2D hybrid airfoil



② HYBRID WING
- Extrude hybrid airfoil ⊥ to L.E.
- Chop ends off
- Rotate model to angle of attack



③ FLOWFIELD
- Run viscous CFD flow simulations
- Match range of full-scale attachment line location at model centerline
- Use angle of attack, flap deflection or combination of both to do so

④ Flow separation and Tunnel load limits acceptable?

NO: Redesign 2D hybrid to alleviate load

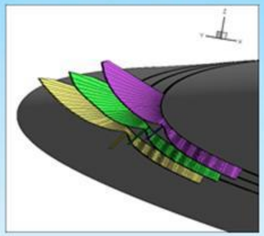
YES

⑤ Spanwise variation acceptable?

NO: Redesign 3D hybrid wing using spanwise load control techniques

YES

⑥ ICE SHAPES
- Input CFD solution LEWICE3D to calculate 3D hybrid wing ice shapes

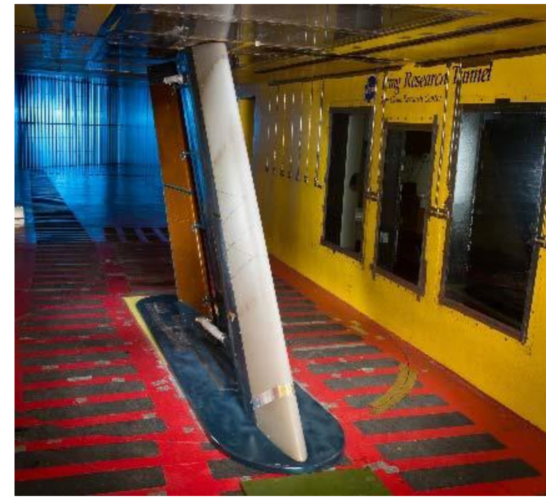


⑦ FINAL CHECKS
- Icing scaling needed? (if significant differences between icing wind tunnel and flight conditions)
- Model loads within tunnel limits?
- Enough flap margin? (before flow separation)

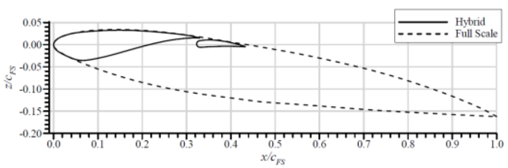
Hybrid Wing Model Design Method (3 of 3)

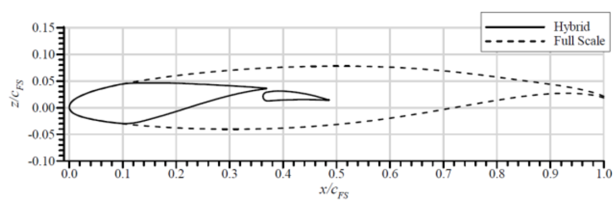
Inboard Model
(20% span)

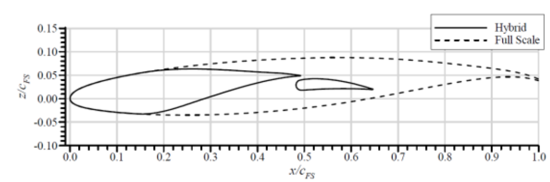
Midspan Model
(64% span)



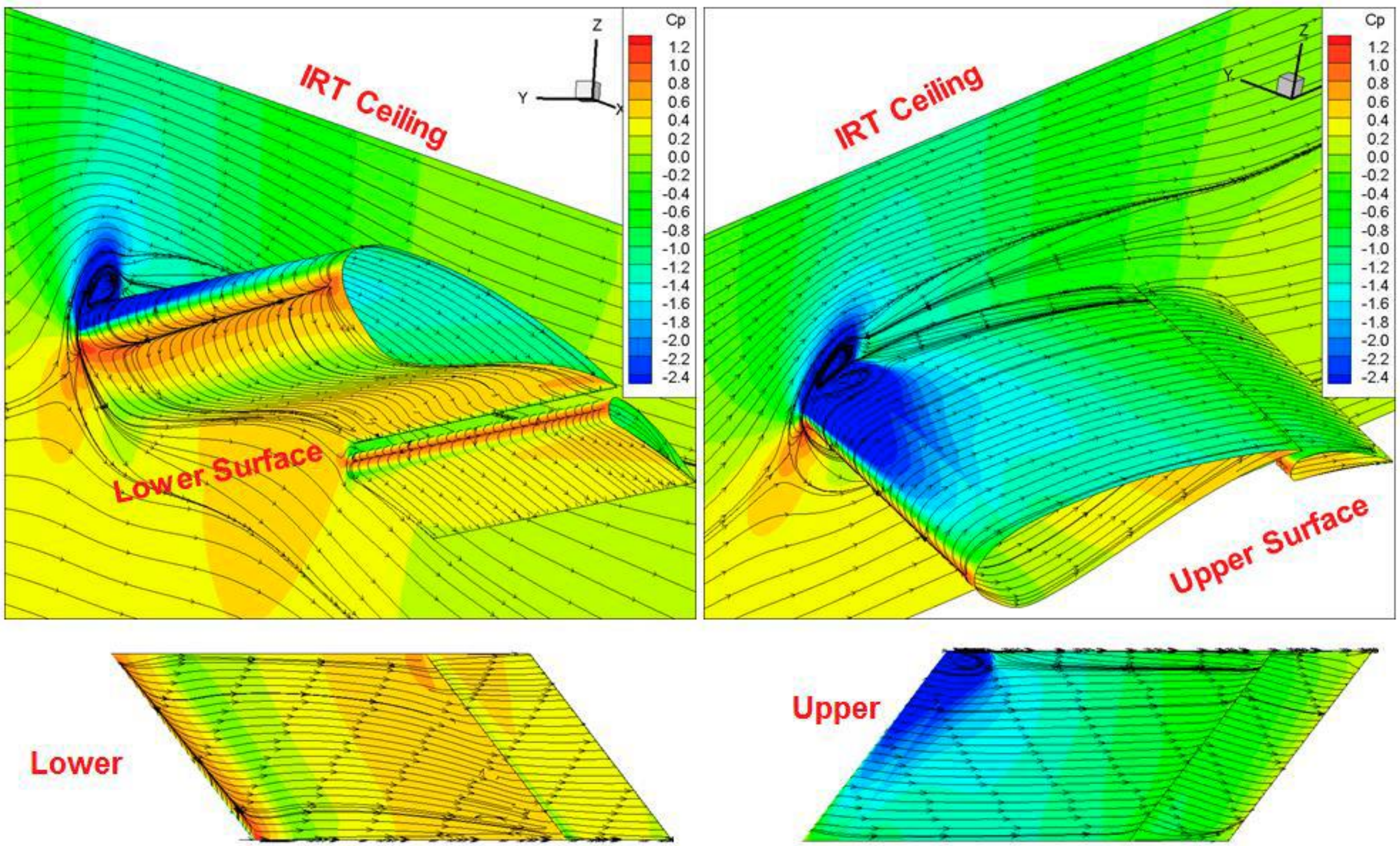
Outboard Model
(83% span)





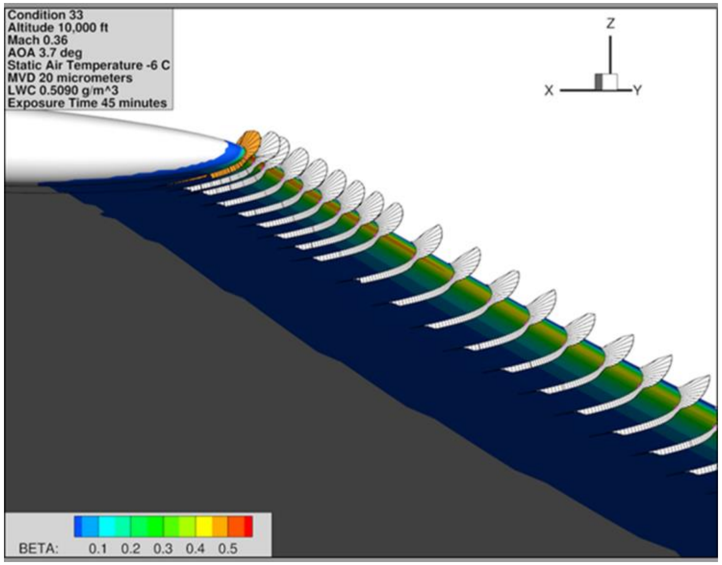


CFD Simulations of the Hybrid Model in the IRT

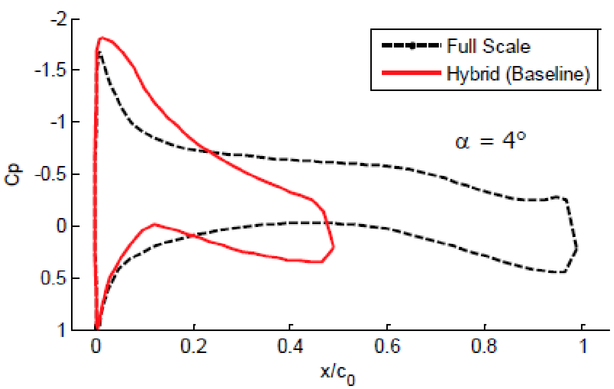


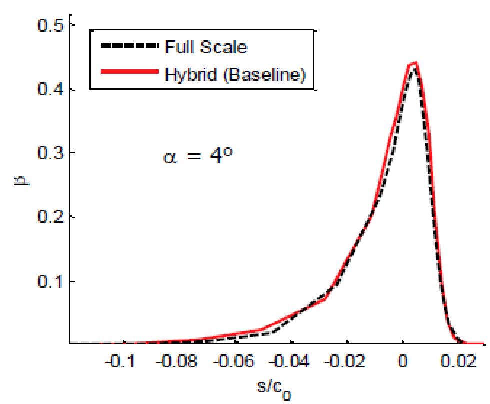
Hybrid wing RANS solution showing spanwise variation: $\alpha = 3.67^\circ$, $\delta = 6^\circ$, V = 119.41 m/s, Re=3.45×10^7

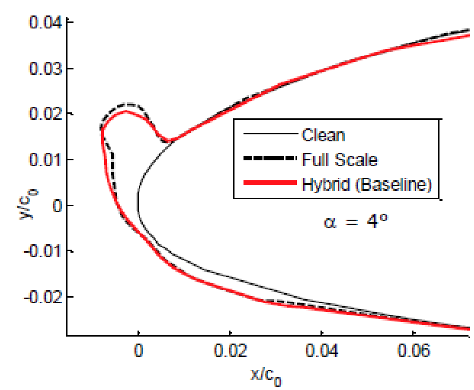
Comparison of Hybrid Ice Shape with Full Scale Ice Shape



- In evaluating the hybrid design, comparisons between the hybrid model and the full scale model are made to guide the development of the hybrid model.
- In the early stages results from 2D analyses are made to establish the hybrid profile. (CFD tools and LEWICE)
- In the final stage comparisons are made using 3D analysis methods. (CFD tools and LEWICE3D)

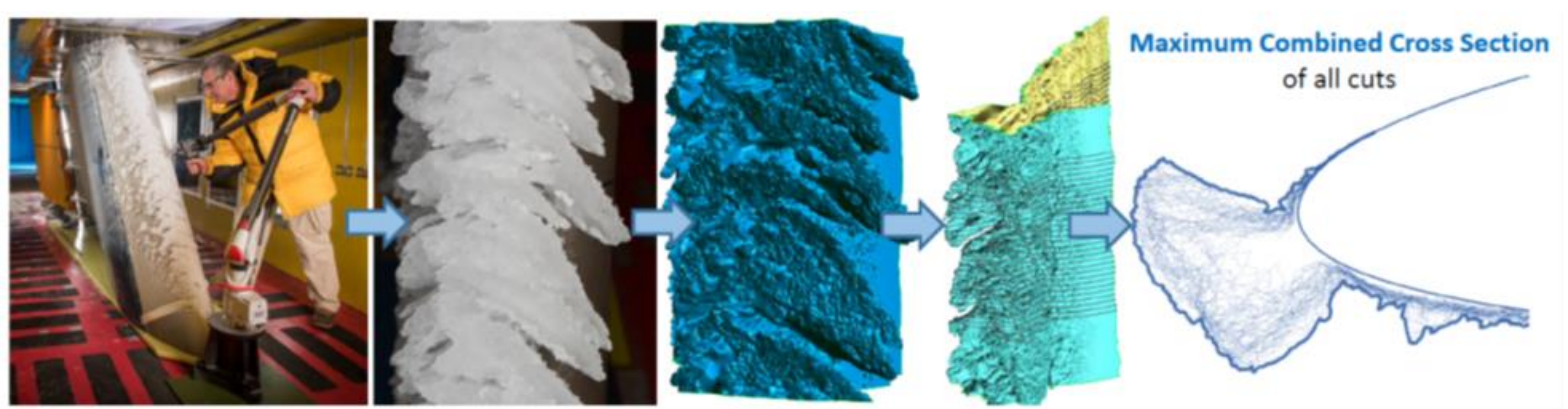




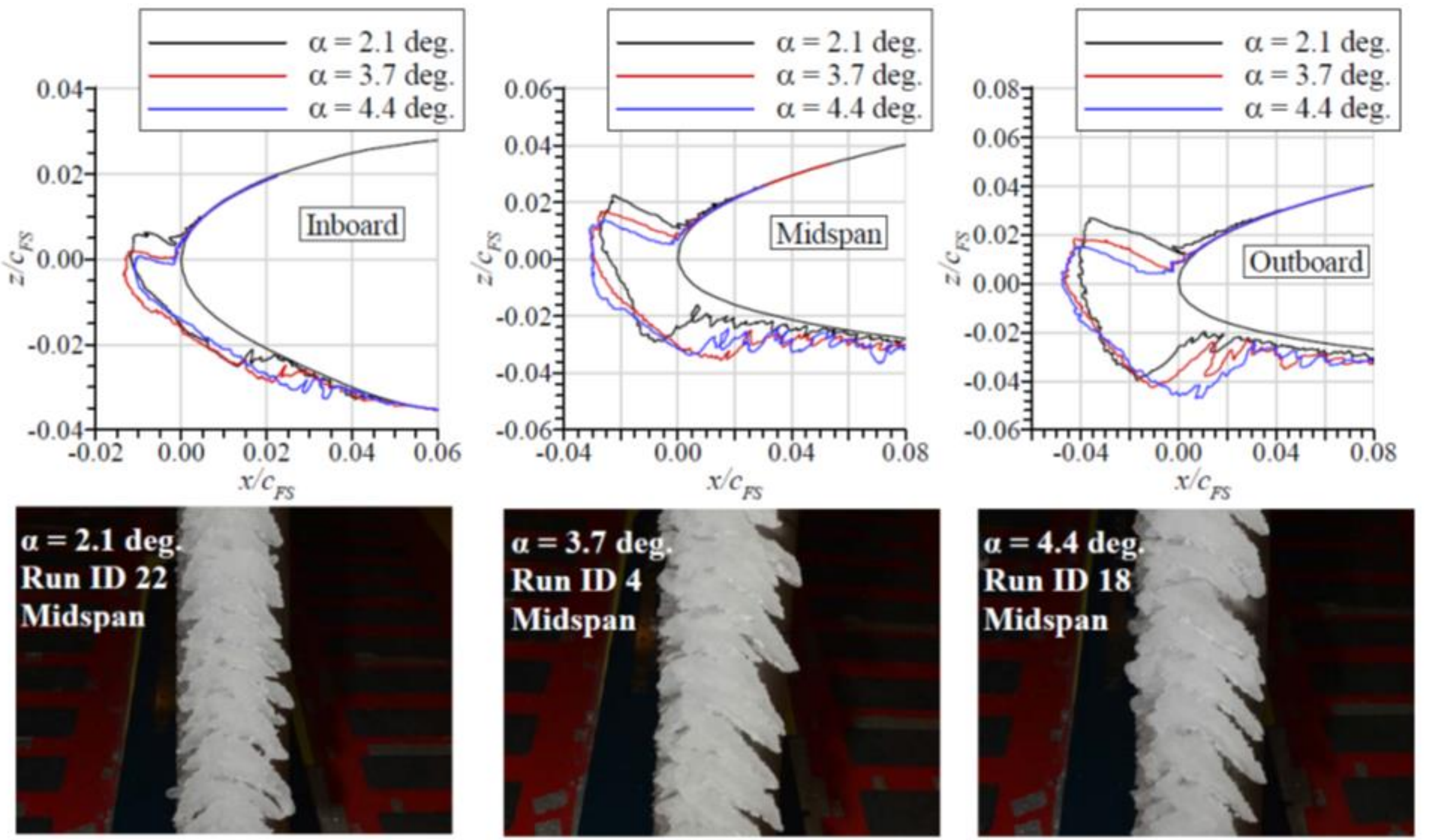


Ice Shape Generation and Documentation in the IRT

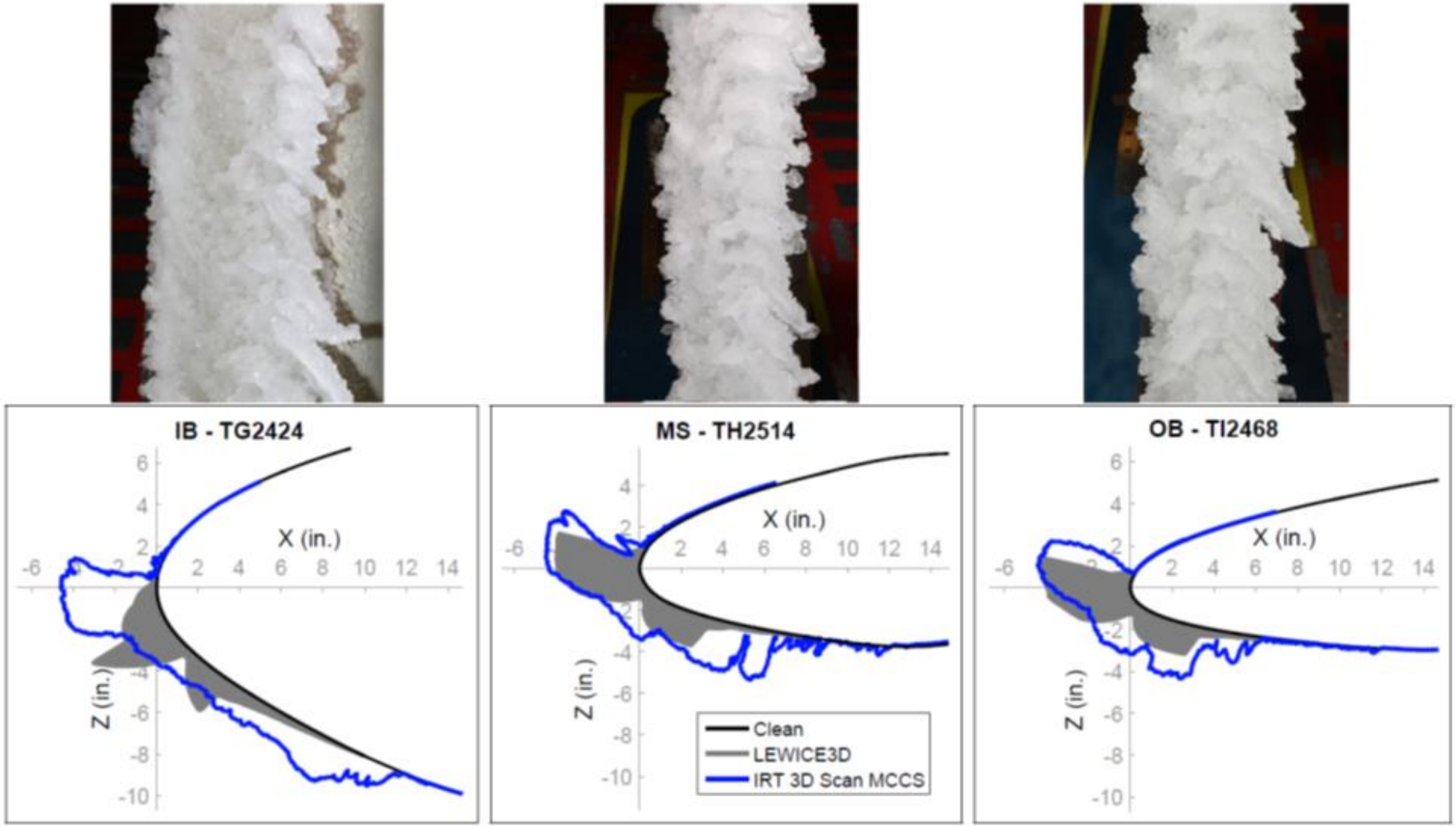
- Ice accretion testing on the Inboard, Midspan and Outboard models was performed in a series of IRT campaigns in 2015.
- Data collected included photographs, laser scanned ice shapes, and ice mass measurements
- The scanned ice shape data was used to develop artificial ice shape models for testing in the low-Re WSU wind tunnel and the high-Re ONERA F1 wind tunnel



Ice Shape Generation and Documentation in the IRT



IRT Ice Shape Results and LEWICE3D Comparisons

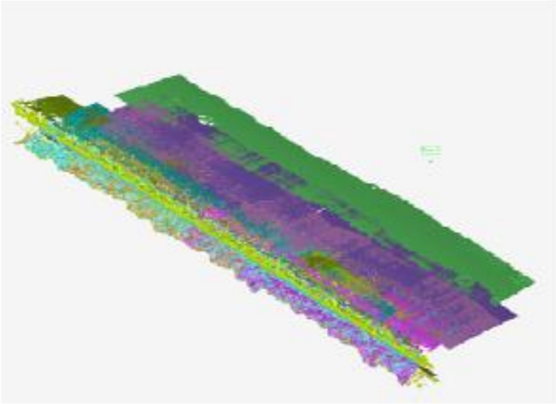


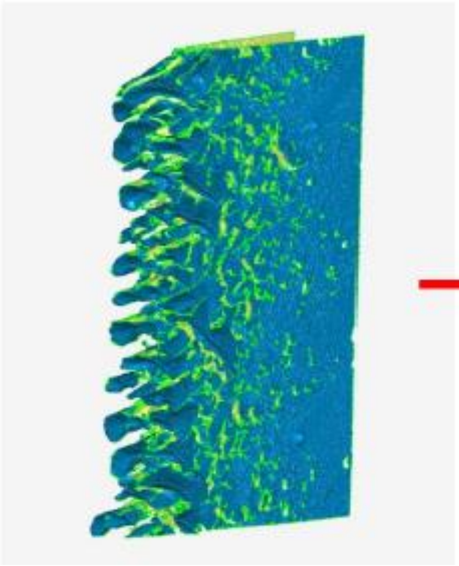
(a) Inboard model run TG2424. (b) Midspan model run TH2414. (c) Outboard model run TI2468.

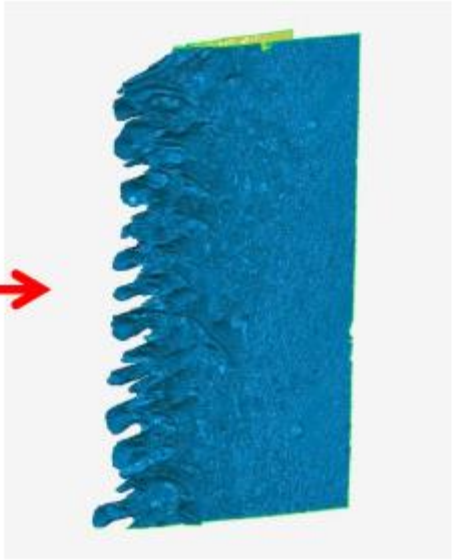
Ice Scan Data Processing Procedure

The IRT scanner data processing procedure consisted of the following five steps:

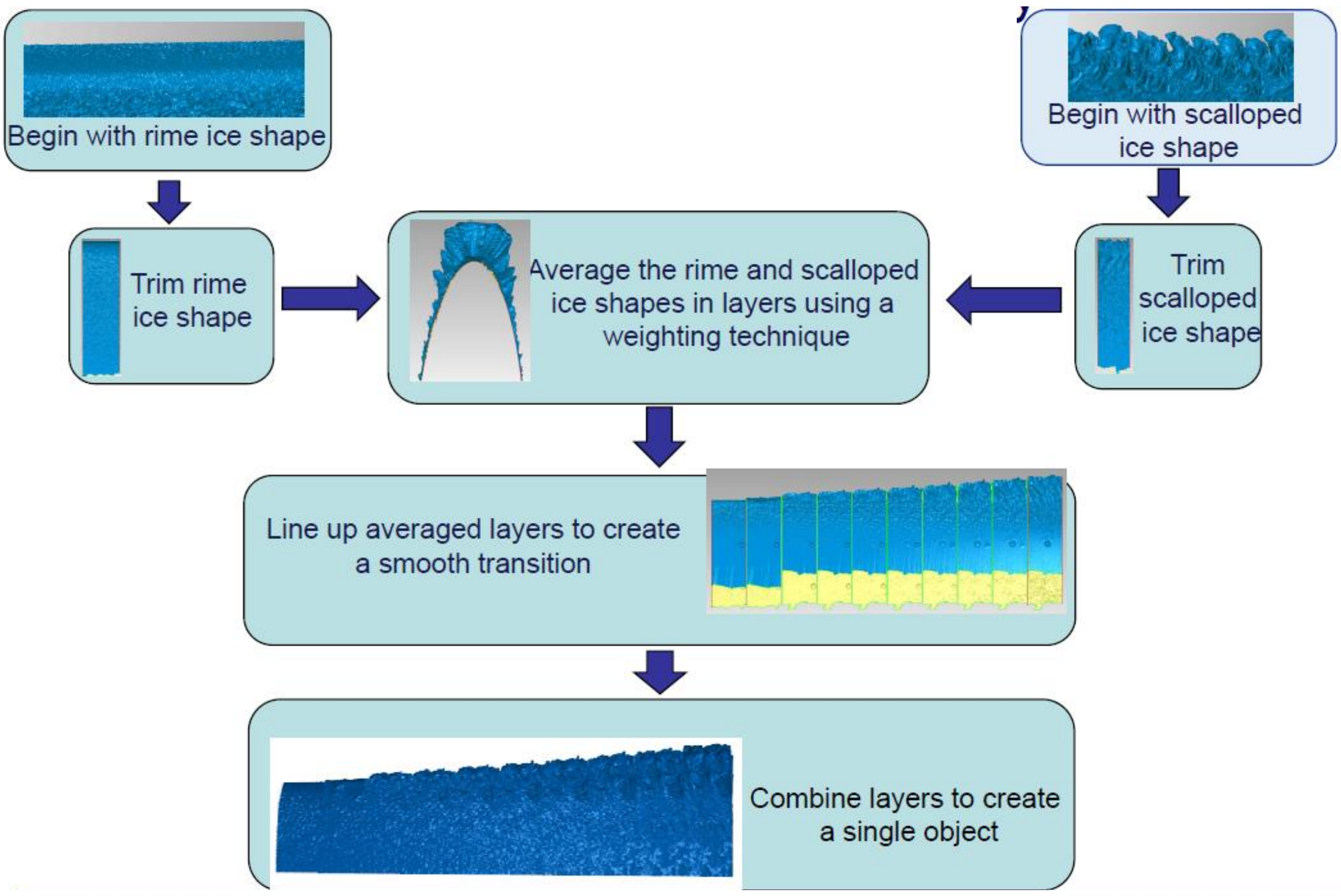
1. Align/combine scan passes
2. Reduce data set
3. Wrap surface
4. Repair mesh/fill holes
5. Coordinate transformation



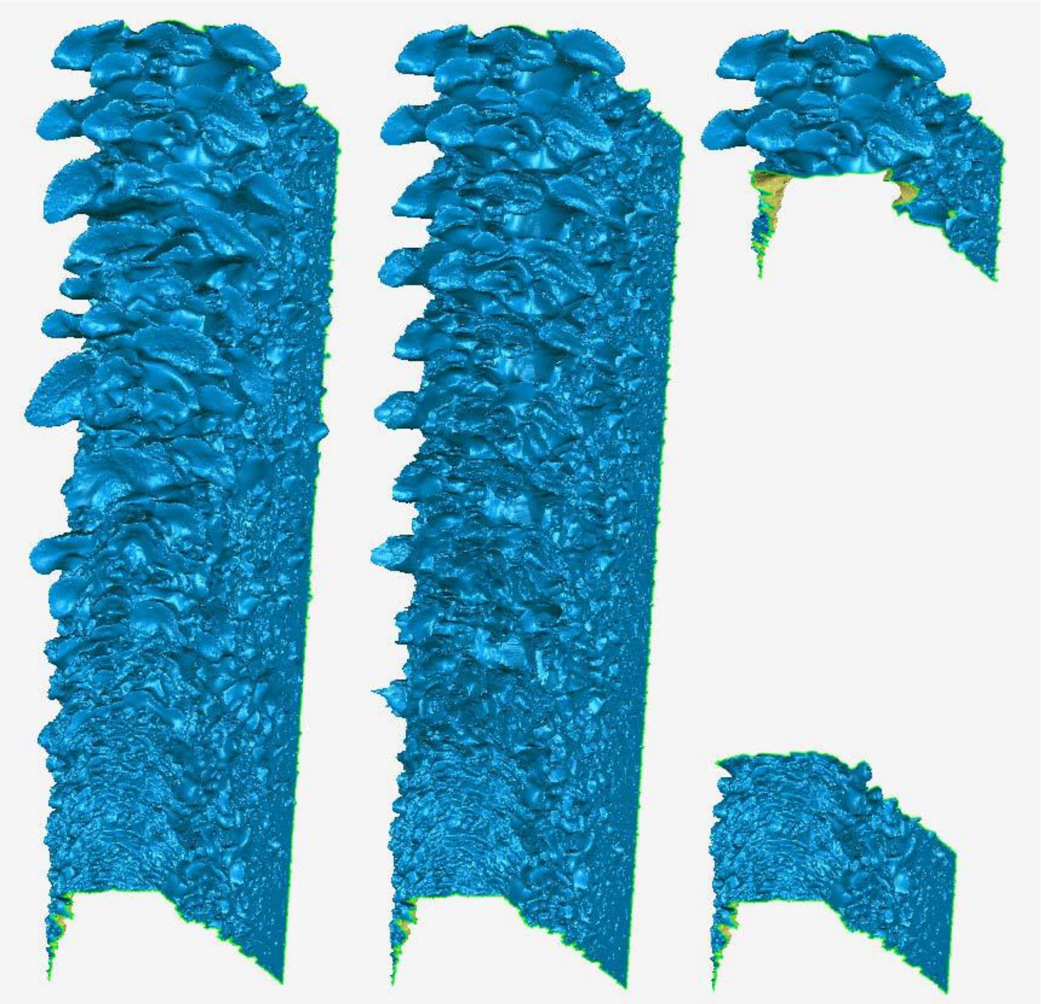




Ice Interpolation Methodology

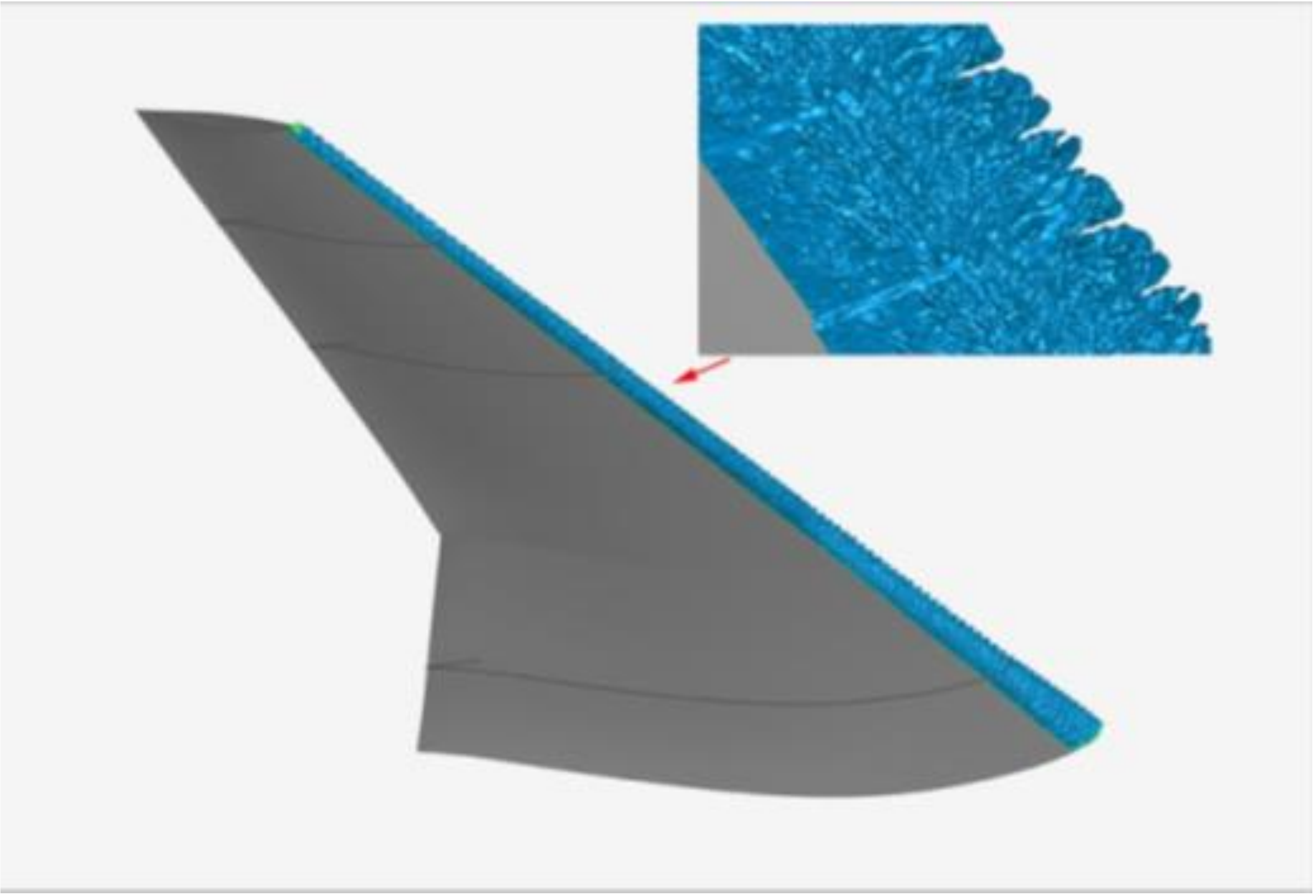


Comparison of Interpolation Method to Real Ice



Full Scan Interpolated Ice

Full Span Ice Shape Based upon Inboard, Midspan, and Outboard Scanned Ice Shape Data

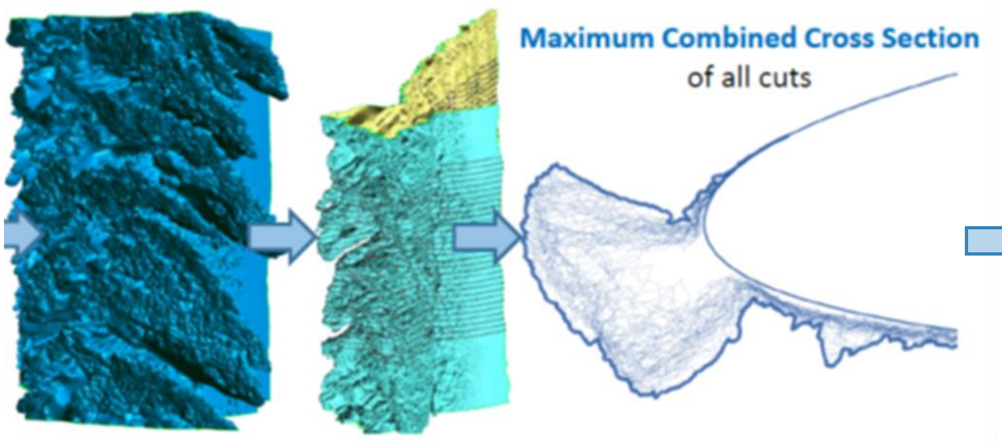


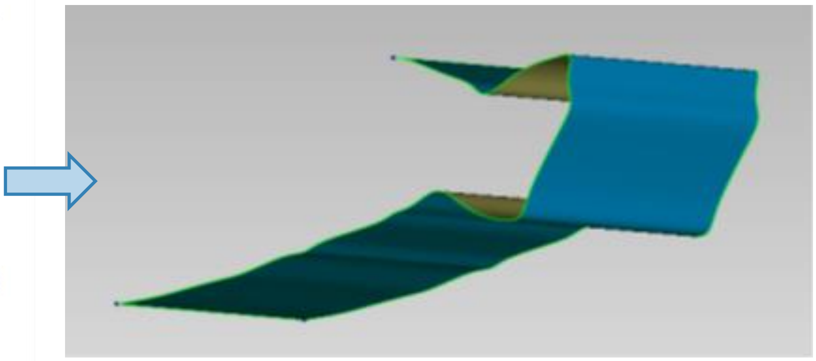
Low Fidelity Ice Shape Generation

Low fidelity ice shapes can be made from several sources

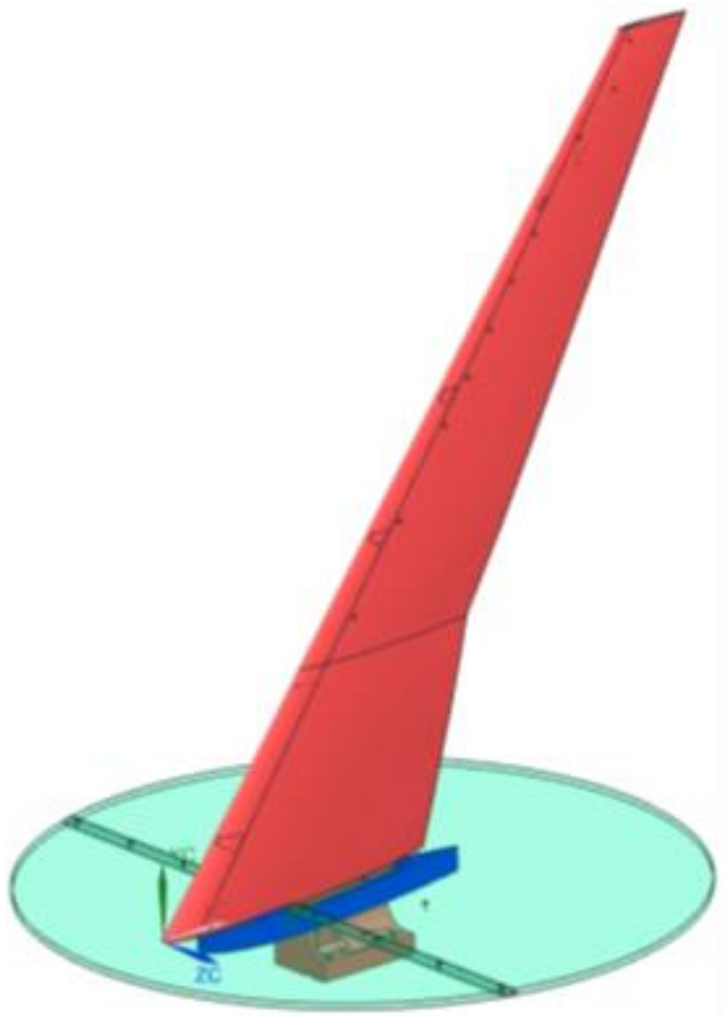
- Maximum Combined Cross Section
- LEWICE3D
- Simple Geometric Shapes

Low fidelity shapes are typically smooth but can be modified to include roughness effects with artificial roughness, e.g. grit

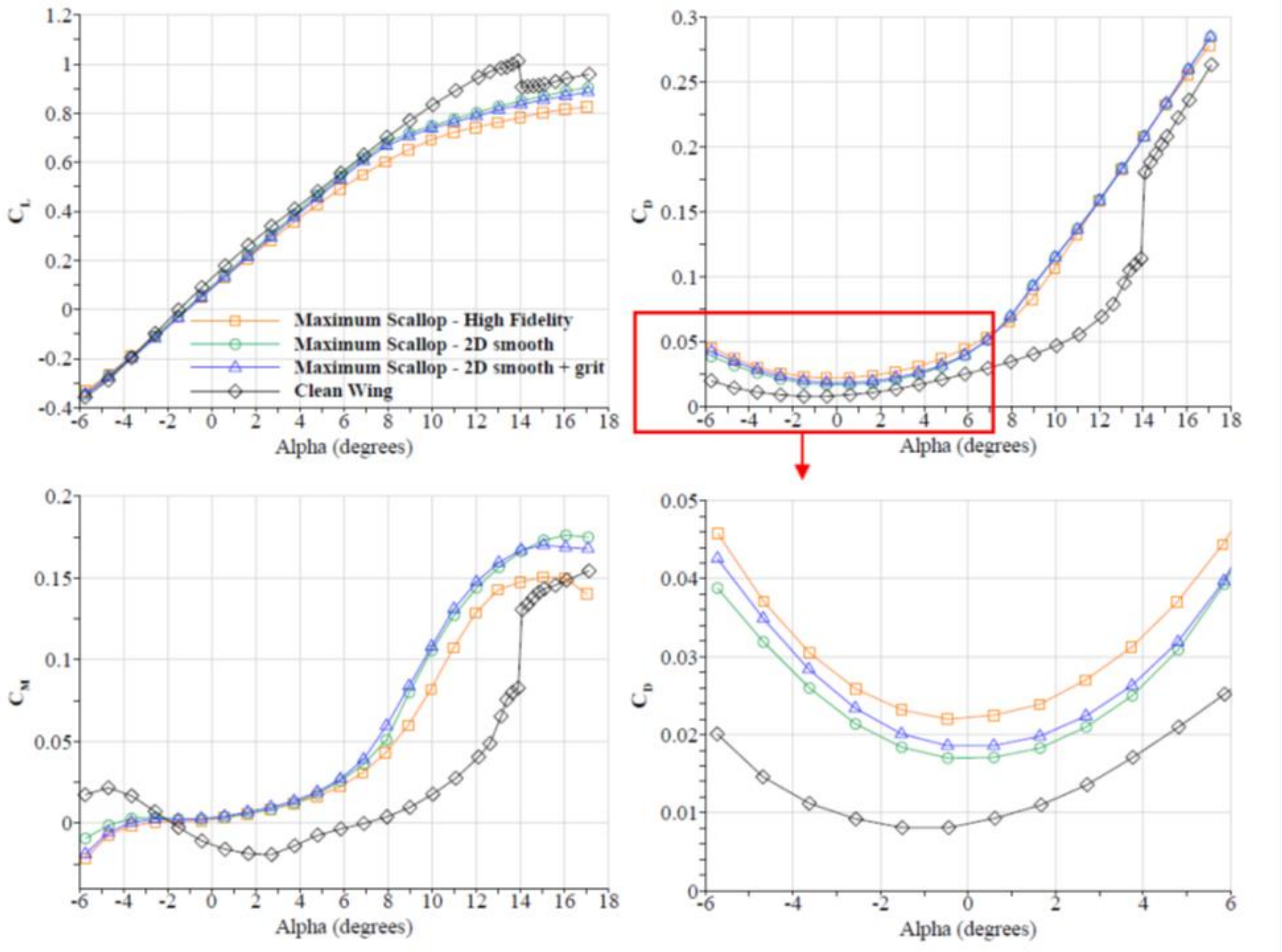




Artificial Ice Shape Installed on the CRM65 Model in the WSU Lo-Re Wind Tunnel



Force Balance Data for Re = 1.6×10^6 and M = 0.18.



Current Status

- Results from the IRT testing and 2 campaigns in the Lo-Re WSU wind tunnel have been presented at the past two AIAA Aviation Conferences; Papers describing those efforts are publicly available
- Some initial efforts at CFD analysis of the aerodynamics of the ice shapes is currently underway
- The first campaign in the High-Re ONERA F1 wind tunnel was just completed this past May
- Follow up aero test campaigns are being planned for both the WSU and ONERA F1 wind tunnels

Concluding Remarks (1/2)

- Hybrid wing models can be developed to enable ice accretion testing on large scale wing leading edge geometries.
- A method has been created to document highly detailed three-dimensional ice shape geometries.
- A method has been created to extend the actual measured geometries to other spanwise locations across a wing model and produce realistic representations of an iced wing configuration.
- Scaling methods developed for straight and swept wing geometries are critical tools to aid in test matrix development for large scale models.
- CFD analysis of wings and wing sections both with and without tunnel walls are critical elements to enable the design of large scale models to be tested in the IRT which will accurately represent the icing environment for such models.
- Computational ice accretion simulation of complete wings and associated icing tunnel wing section models is a critical element for creation such models.

Concluding Remarks (2/2)

- Comparison of the highly complex ice shapes generated on a swept wing model to ice shapes generated in an ice accretion code, no matter how realistic such computational results might be, is a difficult activity. New methods for making such comparisons are required for assessment of the computational tools.
- Aerodynamic data indicates that for large ice shapes, there is very little to no influence of Reynolds number on lift, drag, and pitching moment. For smaller ice shapes, such as rime ice geometries, there can be a difference in drag results as a function of Reynolds number. There are definitely differences due to Reynolds number for clean airfoil configurations and so assessing performance losses at different Reynolds numbers must be done with that result in mind.
- There are differences in performance characteristics between high fidelity and low fidelity ice shapes. 2D smooth configurations can be made to more closely match high fidelity aerodynamic results with the addition of grit to the 2D smooth configuration.

Acknowledgements

This report is a summary of a large body of work that has been conducted over the past few years. As such, the data and commentary for this report has been taken from many of the reports cited by the authors. In many cases, it was best to use the original authors words directly rather than to reinterpret their work.

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